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MATRIX COIL FOR GENERATING A VARIABLE MAGNETIC FIELD

BACKGROUND OF THE INVENTION

[0001] The present invention relates generally to matrix coils for generating variable magnetic fields, and more particularly to magnetic resonance imaging (MRI) devices including matrix coil structures.

[0002] Coil structures for generating magnetic fields are known. Exemplary coil structures include those described in U.S. Patent No. 5,554,929 (the "'929 Patent" hereafter) and U.S. Patent No. 5,530,355 (the "'355 Patent" hereafter), which are incorporated by reference herein in their entirety. Other configurations also exist.

[0003] Known coil structures have been used generate magnetic fields for medical imaging devices, such as magnetic resonance imaging (MRI) devices. In typical MRI device applications, the magnetic fields generated by a plurality of coil structures are combined to generate a target magnetic field for imaging a volume. In particular, each of the plurality of coil structures is positioned in a particular pre-selected location during a manufacturing process, such that, during operation of the MRI device, each of the plurality of coil structures generates one of a main magnetic field, a gradient field, and a higher order shim field, the combination of which results in the target magnetic field.

[0004] As the pre-selected location of the coil structures is set during the manufacturing process, known MRI devices do not have the ability to make substantial changes in the target magnetic field. Thus, the adjustability and configurability of known MRI devices is limited. Hence, a need exists for an improved coil structure, particularly for use in MRI devices.

BRIEF SUMMARY OF THE INVENTION

[0005] According to one embodiment of the present invention, a matrix coil for generating a variable magnetic field is provided, including a plurality of loops arranged in a series so as to have a substantially common axis and segmented into at least one arc-shaped segment, a variable current source for each of the arc-shaped segments, and a controller. The controller is configured to selectively vary an amount of current provided to each of the arc-shaped segments by the variable current sources so as to achieve a variable base field, one or more variable gradient fields, and one or more variable second order shim fields.

[0006] According to another embodiment of the present invention, a method of generating a variable magnetic field is provided. The method includes steps of supplying a current to each of a plurality of arc-shaped segments within each of a plurality of loops, and selectively varying the supplied current provided to each of the plurality of arc-shaped segments. The plurality of loops are arranged in a series so as to have a substantially common axis, and the supplied current is selectively varied to achieve a variable base field, one or more variable gradient fields, and one or more variable second order shim fields.

[0007] According to another embodiment of the present invention, a magnetic resonance imaging device (MRI) is provided, including means for generating a variable base field, one or more variable gradient fields, and one or more variable second order shim fields, means for supplying a current to the means for generating so as to achieve a target field for an imaging region of interest, and means for determining a required current to achieve the target field for the imaging region of interest.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Figure 1 is a block diagram of a coil structure according to an embodiment of the present invention.

[0009] Figure 2 is a block diagram of a coil structure with an array of current elements according to another embodiment of the present invention.

[0010] Figure 3 is a block diagram of a coil structure with series connected arc-shaped segments according to another embodiment of the present invention.

[0011] Figure 4 is a block diagram of a target magnetic field at a sampling point according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0012] Reference will now be made in detail to presently preferred embodiments of the present invention. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0013] A matrix coil for generating a variable magnetic field according to a first embodiment of the present invention is shown in the block diagram of Figure 1. The matrix coil includes a plurality of loops 105, 115, 125 arranged in a series so as to have a substantially common axis 160, each of the plurality of loops 105, 115, 125 being segmented into arc-shaped segments as shown. By way of example, loop 105 is shown with arc-shaped segments 130, 140, 170. It should be appreciated that each loop in the plurality of loops 105, 115, 125 may be segmented into any number of arc-shaped segments (e.g., one or more arc-shaped segments per loop 105, 115, 125), and the number of arc-shaped segments in a given loop 105, 115, 125 may vary from one loop to another. Preferably, the arc-shaped segments in consecutive loops are offset in a radial direction from one another, such as arc-shaped segments 130 and 150 depicted in Figure 1. Other configurations, such as

arc-shaped segments in consecutive loops being substantially aligned are also contemplated.

[0014] While the specific number of loops and arc-shaped segments may vary, according to one preferred embodiment of the present invention, the matrix coil includes at least 32 loops, each of the at least 32 loops being segmented into at least 8 arc-shaped segments. The plurality of loops may be arranged about a substantially cylindrical substrate 199 as shown, preferably having a diameter of at least 70 cm and a length of at least 200 cm.

[0015] The matrix coil further includes a variable current source 110 for each of the plurality of arc-shaped segments, such as a multi-channel amplifier having individual channels dedicated to respective arc-shaped segments. The variable current source 110 may be coupled to a controller 101, such as a processor or special purpose device (e.g., an application specific integrated circuit (ASIC)), for controlling an amount of current provided to each of the plurality of arc-shaped segments by the variable current source 110. In this regard, the controller 101 may comprise a separate component from the variable current source 110, or the controller 101 and variable current source 110 may be combined into a single integrated unit. Preferably, the controller 101 includes a memory for storing a look-up table listing the amount of current provided to each of the plurality of loops to achieve a target field for an imaging region of interest. In this manner, a target field requirement can be entered into the controller 101, which controls the variable current source 110 to supply the requisite currents listed in the look-up table so as to achieve the target field requirement.

[0016] Preferably, the arc-shaped segments are electrically coupled to the variable current source 110 by a plurality of current leads 120 arranged so as to be substantially parallel to the central axis 160. The current leads 120 arranged so as to be substantially parallel to the central axis 160 in order to

inhibit magnetic interference related to the supply of current to the arc-shaped segments. In this regard, the current leads 120 supplying current to loop 115 and loop 125 are only partially shown for simplicity of illustration. It should further be appreciated that, while only one variable current source 110 is shown, multiple multi-channel amplifiers or the like may be provided depending on the particular implementation at hand.

[0017] As previously noted, the controller 101 is configured to selectively vary an amount of current provided to each of the plurality of arc-shaped segments by the variable current sources so as to achieve a variable base field (B_0), one or more variable gradient fields ($G_x+G_y+G_z$), and one or more variable second order shim fields ($Z_x+Z_y+Z_2+C_2+S_2+Z_3$). According to one embodiment of the present invention, a target field (B_z) for an imaging region of interest is achieved by creating a specific base field (B_0), one or more variable gradient fields ($G_x+G_y+G_z$), and one or more variable second order shim fields ($Z_x+Z_y+Z_2+C_2+S_2+Z_3$) that are combined to create the target field (B_z). By way of example, the controller 101 may selectively vary the amount of current provided to each of the plurality of arc-shaped segments in accordance with a discrete approximation of a gradient current density stream function. This gradient current density stream function may be used to calculate the values stored in the previously described look-up table, or be used to calculate requisite currents "on the fly".

[0018] One such technique involves varying the amount of current provided to each of N arc-shaped segments in accordance with the following equation (see also Figure 4):

$$B_z(r_m) = \frac{\mu}{4\pi}\sum_{n=1}^{N} I_n \oint \frac{d_S\left[\varphi \circ \left(r_n^{'} - r_m\right)\right]_Z}{\left|r_n^{'} - r_m\right|^3} \quad \text{(Equation 1)}$$

where r_m are the m^{th} sample point in the target field, m being an integer greater than 1, and

where $r_n^{'}$ are position current elements ds_n along the n^{th} arc of the N arc-shaped segments, N being an integer greater than 1,

where I_n is the current in the N_{th} arc-shaped segment,

and $[ds_n \times (|r_n^{'} - r_m|)]_z$ is the z component of the vector cross product.

[0019] In the aforementioned Equation 1, the target magnetic field B_z is modified by the sum of the matrix currents according to the Biot-Savart Law. In particular, the control currents of the N matrix elements are determined by a least squares fit of the target field B_z at the sample points m defining the region of interest. More specifically, the target field B_z is set to the gradients X, Y and Z or a mixture as the pulse sequence is executed in real time.

[0020] Additionally, desired variable second order shim field(s) can be achieved by selectively varying the amount of current provided to each of the plurality of arc-shaped segments (e.g., to improve homogeneity across the target field B_z) in accordance with the following equations:

$$I_q = \frac{4\pi}{\mu} \sum_q \sum_m \left(A^T{}_{qm} A_{mn} \right)^{-1} A_{nm}{}^T B z_m \quad \text{(Equation 2)}$$

$$A_{mn} = \oint \frac{ds\left[\varphi \circ \left(r_n^{'} - r_m\right)\right]_Z}{\left|r_n^{'} - r_m\right|^3} \quad \text{(Equation 3)}$$

where $A^T{}_{qm}$ and $A^T{}_{nm}$ are transpose matrices with the columns and rows interchanged

[0021] It should be appreciated that the aforementioned Equations 1-3 are provided for purposes of illustration only. Other control techniques may also be used, as would be readily apparent to one of ordinary skill in the art after reading this disclosure.

[0022] The aforementioned configuration is capable of achieving a variable/adjustable magnetic field for imaging a volume by changing the amount of current provided to each of the arc-shaped segments. As such, the aforementioned configuration provides a greater degree of adjustability than known coil structures. While reconfiguration time (i.e., the time it takes to switch from one target magnetic field to another magnetic field) may vary depending on the implementation specifics, the maximum reconfiguration time may be limited by nerve stimulation limitations of the human body.

[0023] To further improve the variability of the target field (B_z), an array of current elements 210 connected by current leads 120 may be provided, preferably arranged in the configuration shown in Figure 2. In this regard, the array of current elements 210 provides greater control of the magnetic field generated along the z axis. Other configurations are also contemplated, as would be readily apparent to one of ordinary skill in the art after reading this disclosure.

[0024] According to another embodiment of the present invention as shown in Figure 3, two or more arc-shaped segments 330, 340 in different loops (preferably adjacent loops) may be connected in series, such that one channel of the variable current source 110 supplies current to the series connected arc-shaped segments 330, 340. Such a configuration may be applied to all of the arc-shaped segments of the matrix coil, or to only a fraction of the total number of arc-shaped segments. By coupling two or more of the arc-shaped segments 330, 340 in series, the apparent density of arc-shaped segments can be increased (due to two or more arc-shaped segments in different loops), resulting in an increased magnetic field magnitude, without increasing the amount of current provided to any one arc-shaped segment. However, the series connection between the arc-shaped segment 330 and the arc-shaped segment 340 should take place sufficiently outside of the matrix coil as shown in Figure 3, in order to inhibit magnetic

interference related to the series connection. As such, in a preferred configuration, the current leads 320 within the matrix coil are preferably arranged to be substantially parallel to the common axis 160 as much as possible. This may or may not result in a slight offset between the arc-shaped segments 330, 340 as shown in Figure 3.

[0025] The foregoing description of preferred embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The embodiments were chosen and described in order to explain the principles of the invention and its practical application to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.